

First measurement of coherent double neutral-pion photoproduction on the deuteron at incident energies below 0.9 GeV

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Abstract

The total cross sections were measured for coherent double neutral-pion photoproduction on the deuteron at incident energies below 0.9 GeV for the first time. No clear resonance-like behavior is observed in the excitation function for $W_{\gamma d} = 2.38\text{--}2.61$ GeV, where the $d^*(2380)$ dibaryon resonance observed at COSY is expected to appear. The upper limit of the total cross section is found to be $0.071\text{ }\mu\text{b}$ for the dibaryon resonance at $W_{\gamma d} = 2.37$ GeV (90% confidence level) in the $\gamma d \rightarrow \pi^0 \pi^0 d$ reaction. The measured excitation function exhibits a rather flat distribution, which is inconsistent with the existing theoretical calculation for this reaction.

Keywords: Coherent meson photoproduction, Dibaryon resonance, ABC effect

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The internal structure of hadrons is a subject in the non-perturbative domain of the fundamental theory of strong interactions, quantum chromodynamics. The familiar mesons and baryons are composed of $q\bar{q}$ and qqq , respectively. More complex quark configurations beyond these are objects of great interest to investigate the effective degrees of freedom describing hadrons and to understand color confinement. The WASA-at-COSY collaboration has recently reported the isoscalar $d^*(2380)$ resonance with mass $M \simeq 2380$ MeV and width $\Gamma \simeq 68$ MeV, which is observed in the $pn \rightarrow \pi^0\pi^0d$ [1] and $pn \rightarrow \pi^+\pi^-d$ [2] reactions. The first indication corresponding to this resonance was observed in the former reaction by the CELSIUS/WASA collaboration [3]. The resonance may be attributed to an isoscalar $\Delta\Delta$ quasi-bound state, \mathcal{D}_{03} , predicted by Dyson and Xuong [4]. In addition to the $\pi^0\pi^0d$ and $\pi^+\pi^-d$ final states, evidence for the $d^*(2380)$ resonance has been confirmed by the WASA-at-COSY collaboration in the $\pi^0\pi^-pp$ [5], $\pi^0\pi^0pn$ [6], and $\pi^+\pi^-pn$ [7] final states. The SAID partial wave analysis, which incorporates the analyzing power for the quasi-elastic $\vec{n}p \rightarrow np$ scattering measured by the WASA-at-COSY collaboration, also supports the existence of the $d^*(2380)$ resonance with quantum numbers $I(J^\pi) = 0(3^+)$ [8, 9]. These experimental results have stimulated intensive theoretical investigations of \mathcal{D}_{03} [10, 11]. To date, all the observations have been made using pn collisions. Nearly all the measurements were made by the WASA-at-COSY collaboration.

The $d^*(2380)$ resonance should be observable in photoproduction reactions if it exists. The $\gamma d \rightarrow \pi^+\pi^-d$ and $\gamma d \rightarrow \pi^0\pi^0d$ reactions are expected to be of value when studying the production mechanism of the $d^*(2380)$ resonance. It may be produced as an intermediate state in the s channel, and decays into a final state including a deuteron, where no special treatment is required kinematically for the Fermi motion of nucleons. The former reaction was studied by the CLAS collaboration at the Thomas Jefferson National Accelerator Facility. Their preliminary result does not show a peak corresponding to the $d^*(2380)$ resonance [12]. The $\pi^+\pi^-d$ final state includes the isovector ($I = 1$) component, while the $\pi^0\pi^0d$ has just the isoscalar ($I = 0$) component alone. The Kroll-Ruderman contact term is expected to give a large effect in the $\pi^+\pi^-d$ channel, i.e., the $\gamma N\pi^\pm$ coupling is large. This may hide the $d^*(2380)$ contribution in the $\gamma d \rightarrow \pi^+\pi^-d$ yield. Therefore, the $\gamma d \rightarrow \pi^0\pi^0d$ reaction is thought to be the best process to investigate the $d^*(2380)$ resonance in photoproduction.

Two series of meson photoproduction experiments [13] were carried out using the tagged photon beam [14, 15] at the Research Center for Electron Photon Science (ELPH), Tohoku University. The photon beam was produced by a bremsstrahlung process with a carbon fiber from the 0.93 GeV circulating electrons in a synchrotron called the STretcher Booster (STB) ring [16]. The tagging energy of the photon beam ranged from 0.57 to 0.88 GeV. The target used in the experiments was liquid deuterium with a thickness of 45.9 mm. The incident photon energy gives a γd center of mass energy, $W_{\gamma d}$, from 2.38 to 2.61 GeV, and the lowest photon energy corresponds to the centroid of the $d^*(2380)$ resonance.

All the final-state particles in the $\gamma d \rightarrow \pi^0\pi^0d$ reaction were measured using an electromagnetic (EM) calorimeter complex, FOREST [17]. FOREST consists of three different EM calorimeters: the forward, central, and backward calorimeters consisting of 192 pure CsI crystals, 252 lead scintillating fiber modules, and 62 lead glass Cherenkov counters, respectively. A plastic scintillator (PS) hodoscope is placed in front of each calorimeter to identify the charged particles. The solid angle of FOREST is approxi-

mately 88% in total. The typical tagging rate was 2.8 MHz, and the photon transmittance (so-called tagging efficiency) was approximately 42% [14]. The trigger condition of the data acquisition (DAQ) is described elsewhere [17]. The average trigger rate was 1.1 kHz, and the average DAQ efficiency was 85%.

Events detected in the final state containing four neutral particles and a charged particle were selected. Each neutral pion in the $\gamma d \rightarrow \pi^0 \pi^0 d$ reaction was identified via its decay into $\gamma\gamma$. Photons were detected as a set (cluster) of hit calorimeter modules without any responses of the hit PSs in the front hodoscope. The details of making clusters in FOREST are described in Ref. [17]. The time difference between every two neutral clusters of four was required to be less than $3\sigma_t$, where σ_t denotes the time resolution for the difference depending on the modules and their measured energies for the two clusters. Deuterons in the final state were detected with the forward hodoscope called SPIDER, and the direction of emission was determined by the hit PSs. Note that the response of the corresponding calorimeter called SCISSORS III was not required. The time delay from the average time response between the four neutral clusters was required to be larger than 1 ns. The energy measured with SPIDER was required to be greater than $2E_{\text{mip}}$, where E_{mip} denotes the energy that the minimum ionizing particle deposits in a PS. The momentum of deuterons was calculated from the measured time delay assuming that the charged particles had the mass of the deuteron.

A kinematic fit with six constraints (6C) was applied for the further event selection of the $\gamma d \rightarrow \pi^0 \pi^0 d$ reaction. The kinematic variables in the fit were the incident photon energy, the three momenta of the five final-state particles, and the reaction vertex point. Even though FOREST did not have a vertex counter, the (x, y) intensity map of the photon beam was measured using a beam-profile monitor [15] day by day. The measured variable and its resolution for the $x(y)$ -component of the vertex point was assumed to be the same as the centroid and width of the $x(y)$ distribution of the photon beam at the target position. Because the attenuation of the photon beam flux was negligibly small passing through the liquid deuterium target, the measured variable and its resolution for the z -component was assumed to be the same as the center and thickness(σ) of the target. The required constraints were energy and three-momentum conservation between the initial and final states and two $\gamma\gamma$ invariant masses (the neutral-pion rest mass, m_{π^0}). Events in which the χ^2 probability was higher than 0.1 were selected. Because accidental coincidence events exist between the photon-tagging counter, STB-Tagger II [14], and FOREST, sideband background subtraction was performed.

The 6C kinematic fit is effective at selecting the $\gamma d \rightarrow \pi^0 \pi^0 d$ reaction. Fig. 1 shows the correlation between the measured energy by a first-layer PS in SPIDER and the fitted momentum of a deuteron. Only the locus corresponding to the deuteron is observed after the kinematic fit. Fig. 2(a) shows the typical $\pi^0 \pi^0$ invariant mass ($m_{\pi\pi}$) distribution. The $m_{\pi\pi}$ distribution for the real data is quite different from that for the isotropic generation of the three final-state particles. No enhancement corresponding to the ABC effect [18] is observed in the lower-mass region close to $2m_{\pi^0}$. Conversely, a strong enhancement is observed in the higher-mass region. Fig. 2(b) shows the typical $\pi^0 d$ invariant mass ($m_{\pi d}$) distribution. No significant difference between the real data and the simulation is observed in the $m_{\pi d}$ distribution.

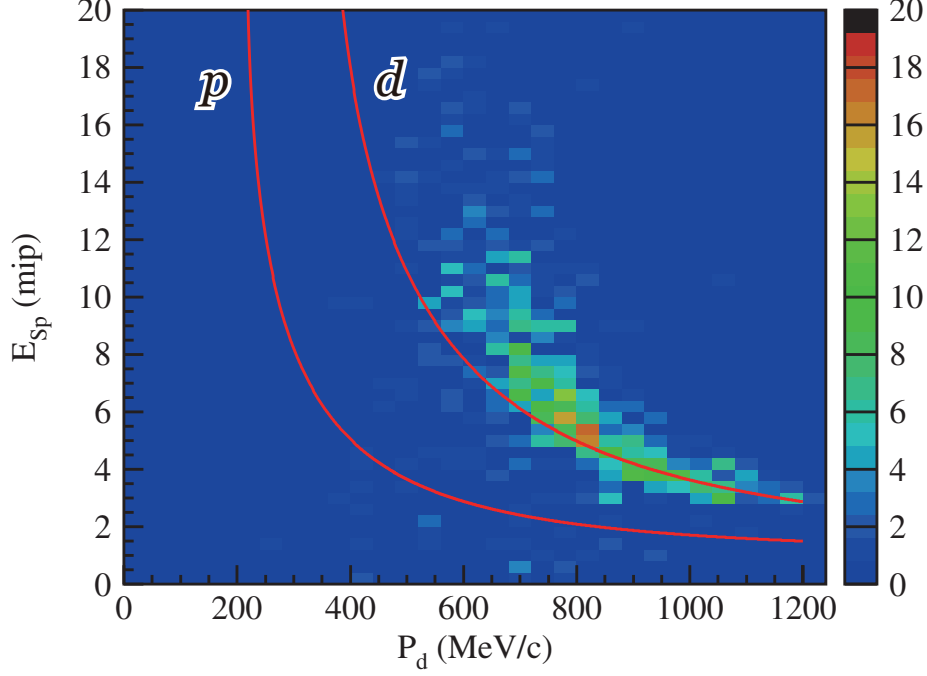


Figure 1: Correlation between measured energy by a first-layer PS in SPIDER and fitted momentum of the deuteron. The lower and upper curves show the loci corresponding to correlations for protons (p) and deuterons (d), respectively.

The total cross section of the $\gamma d \rightarrow \pi^0 \pi^0 d$ reaction can be obtained from the equation

$$\sigma = \frac{N_{\pi^0 \pi^0 d}}{N'_\gamma N_\tau \eta_{\text{acc}} \{\text{BR}(\pi^0 \rightarrow \gamma\gamma)\}^2}, \quad (1)$$

which uses the number of events for the $\gamma d \rightarrow \pi^0 \pi^0 d$ reaction, $N_{\pi^0 \pi^0 d}$, the effective number of incident photons, N'_γ , the number of target deuterons per unit area, $N_\tau = 0.237 \text{ b}^{-1}$, the acceptance of the final state $\pi^0 \pi^0 d \rightarrow \gamma\gamma\gamma d$ detection, η_{acc} , and the branching ratio of the neutral pion to the two-photon decay, $\text{BR}(\pi^0 \rightarrow \gamma\gamma)$. The number of incident photons, N_γ , is determined by multiplying the number of tagging signals after the counting-loss correction by the corresponding photon transmittance. The N'_γ is obtained additionally multiplying N_γ by the DAQ efficiency. The acceptance of $\gamma\gamma\gamma d$ detection is estimated by a Monte-Carlo simulation based on Geant4 [19]. Here, the total cross section as a function of the incident energy is assumed to be flat. To reproduce the measured $m_{\pi\pi}$ distribution, the $m_{\pi\pi}$ distribution for generated events is assumed to have an additional dependence from isotropic generation:

$$P = \left(\frac{m_{\pi\pi} - m_{\pi\pi}^{\min}}{m_{\pi\pi}^{\max} - m_{\pi\pi}^{\min}} \right)^n \quad (2)$$

with $n = 1.7$, where $m_{\pi\pi}^{\max}$ and $m_{\pi\pi}^{\min}$ denote the maximum and minimum values for $m_{\pi\pi}$,

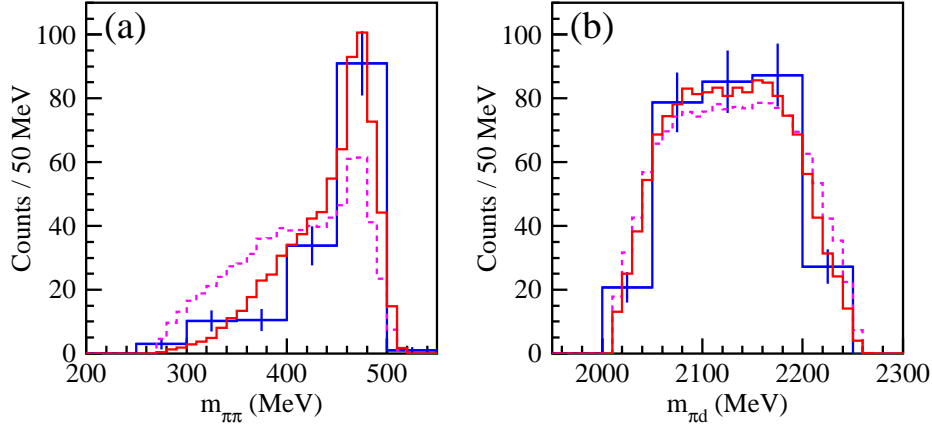


Figure 2: (a) $\pi^0\pi^0$ and (b) π^0d invariant mass distributions at $W = 2.39$ GeV. The data points (blue) are compared with the simulation results. The dashed histogram (magenta) shows the results for isotropic event generation, and the solid histogram (red) shows the results for $n = 1.7$ (see text). Normalizations of the simulation results are the same for (a) and (b).

respectively, at the fixed incident photon energy.

Because the statistic was limited, the tagging channels were divided into 16 groups, and the total cross section was obtained for each group. Fig. 3 shows the total cross section σ for the $\gamma d \rightarrow \pi^0\pi^0d$ reaction as a function of $W_{\gamma d}$. The total cross section is rather flat, and a clear resonance-like behavior is not observed in the excitation function for $W_{\gamma d} = 2.38$ – 2.61 GeV,

To estimate the systematic uncertainty of event yields, we varied the lower limit of event selection in the kinematic fit, and the uncertainty (σ) was found to range from 5.0% to 9.0% depending on the tagging-energy group. We also tried a kinematic fit excluding the vertex point from the running variables and fixing it to $(0, 0, 0)$. The difference (σ) between the two kinematic-fit results is 0.5%–5.7%. To estimate the systematic uncertainty of the acceptance, we changed the $m_{\pi\pi}$ distribution for event generation in the simulation. The n parameters corresponding to the realistic $m_{\pi\pi}$ distributions give the uncertainty (σ) from 0.1% to 0.5%. The uncertainty in the acceptance from the uncertainty in the FOREST coverage is 1.6%–4.7%. The uncertainty in the deuteron detection efficiency is 0.3%–3.9% owing to the uncertainty in the density of the vacuum chamber surrounding the liquid deuterium target. The normalization uncertainties resulting from the number of target deuterons and the number of incident photons are 1% and 1.5%–1.9%, respectively. The total systematic uncertainty is obtained by combining all the uncertainties described above in quadrature. The total systematic uncertainty as a function of $W_{\gamma d}$ is also plotted in Fig. 2.

As shown in Fig. 2, a significant peak is not observed at $W = 2.37$ GeV. The $d^*(2380)$ contribution was estimated by fitting the function

$$\sigma(W_{\gamma d}) = \frac{\text{BW}(W_{\gamma d})}{\text{BW}(2.37 \text{ GeV})} \sigma_{d^*} + \sigma_0 \quad (3)$$

to the data, where $\text{BW}(W_{\gamma d})$ denotes the relativistic Breit-Wigner function [20] corre-

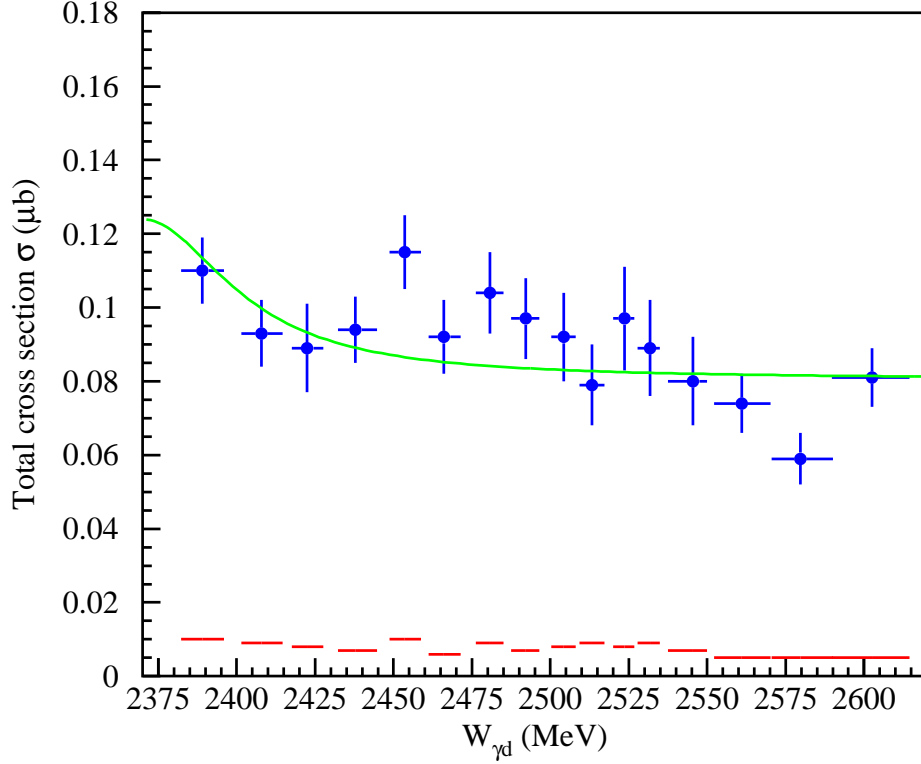


Figure 3: Total cross section σ as a function of $W_{\gamma d}$. The upper points (blue) show the obtained σ . The horizontal error of each point shows the coverage of incident photon energy, and the vertical error shows the statistical error of σ . The lower histogram (red) shows the systematic errors (see text for details). The data are compared with a function (green) expressed by the sum of the constant ($0.081 \mu\text{b}$) and expected $d^*(2380)$ contributions with a relativistic Breit-Wigner shape with $W = 2.37 \text{ GeV}$ and $\Gamma = 68 \text{ MeV}$ ($0.043 \mu\text{b}$ at $W = 2.37 \text{ GeV}$).

sponding to the expected $d^*(2380)$ contribution with a centroid of $M = 2.37 \text{ GeV}$ and a width of $\Gamma = 68 \text{ MeV}$. The χ^2 of the fit is 17.0, and the obtained parameters are

$$\begin{cases} \sigma_{d^*} = 0.043 \pm 0.017 \mu\text{b}, \text{ and} \\ \sigma_0 = 0.081 \pm 0.004 \mu\text{b}. \end{cases} \quad (4)$$

Assuming a higher polynomial function for the background contribution instead of a constant σ_0 , a smaller $d^*(2380)$ contribution is obtained. The upper limit of the total cross section was found to be $0.071 \mu\text{b}$ at $W_{\gamma d} = 2.37 \text{ GeV}$ (90% confidence level).

Egorov and Fix recently reported their calculation of the total cross section for the $\gamma d \rightarrow \pi^0 \pi^0 d$ reaction [21]. For coherent production, the isovector parts in the amplitudes for the $\pi^0 \pi^0$ production on the proton and neutron are canceled. Because the fraction of the isoscalar part is thought to be only 8% of the proton amplitude, the cross section for the coherent production is much smaller than that for the quasi-free $\pi^0 \pi^0$ production on the nucleon ($\sim 10 \mu\text{b}$ at $E_\gamma = 0.60 \text{ GeV}$). Fig. 4 shows the total cross section as a function of the incident energy, E_γ . Even though the measured cross section is of the

same order as that of the calculation, a significant difference is observed at the lowest incident photon energy (0.57 GeV). This may be explained by the larger fraction of the isoscalar part in the excitation of the lower-mass baryons. The $N\Delta$ system is forbidden in the intermediate state of the $\gamma d \rightarrow \pi^0 \pi^0 d$ reaction. Suppose a baryon resonance is produced on a nucleon in the deuteron, the lowest-mass resonance that can decay into $\pi^0 \pi^0 N$ is $P_{11}(1440)$. The center of mass corresponds to an incident photon energy of $E_\gamma = 0.64$ GeV; therefore, it is difficult to explain the difference in the cross sections by just the incorrect fraction of the isoscalar part of the P_{11} excitation. Another possible explanation for this difference is the larger contribution of the sequential π^0 emission $\gamma N \rightarrow \pi^0 \Delta \rightarrow \pi^0 \pi^0 N$ together with deuteron re-combination. The enhancement in the higher-mass region of the $m_{\pi\pi}$ distribution might support this hypothesis. The direct coherent production of the σ meson, which decays into $\pi^0 \pi^0$, may also provide an explanation for the difference.

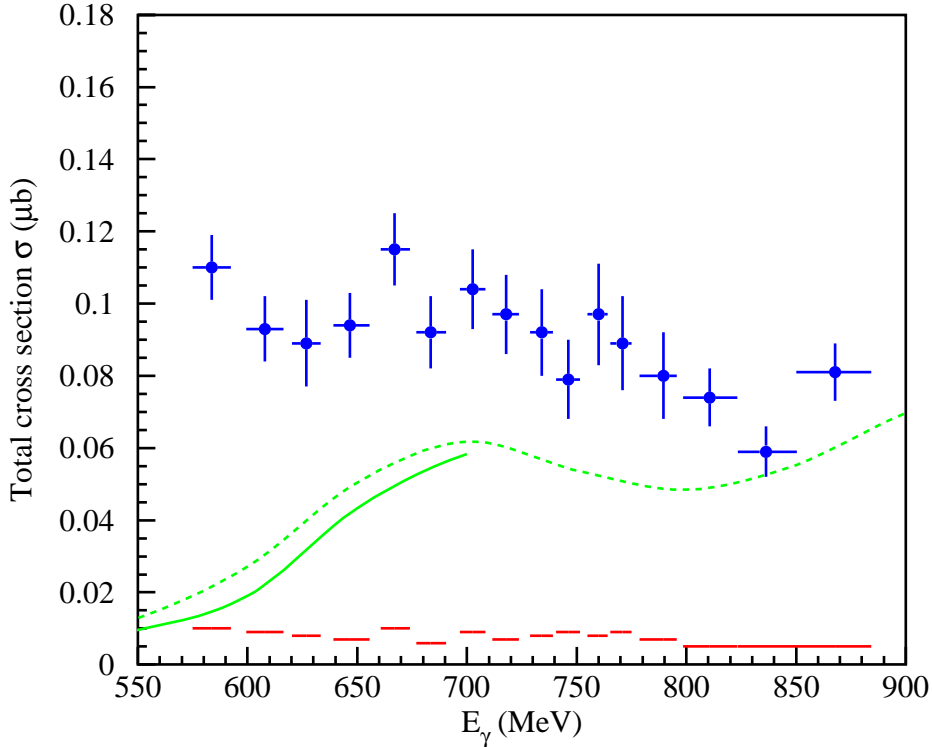


Figure 4: Total cross section, σ , as a function of E_γ . The upper points (blue) show the obtained σ . The horizontal error of each point shows the coverage of the incident photon energy, and the vertical error shows the statistical error of σ . The lower histogram (red) shows the systematic errors (see text for details). The data are compared with theoretical calculations for the $\gamma d \rightarrow \pi^0 \pi^0 d$ reaction given in Ref. [21] (solid) and Ref. [22] (dashed).

The total cross sections for the $\gamma d \rightarrow \pi^0 \pi^0 d$ reaction were measured for the first time using the FOREST detector at ELPH. The incident energy ranged from 0.57 to 0.88 GeV. No clear resonance-like behavior corresponding to the $d^*(2380)$ resonance with

$I(J^\pi) = 0(3^+)$ was observed in the excitation function for $W_{\gamma d} = 2.38\text{--}2.61$ GeV. The upper limit of the total cross section in this reaction was found to be $0.071 \mu\text{b}$ for the dibaryon resonance at $W_{\gamma d} = 2.37$ GeV (90% confidence level). The measured excitation function is rather flat, which is inconsistent with the existing theoretical calculation for the $\gamma d \rightarrow \pi^0 \pi^0 d$ reaction. A further understanding of the isoscalar part of $\pi^0 \pi^0$ production is required.

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